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Key Words

Iron Ore Tailings; Water Content; Frequency Domain Refractometry (FDR)

Research Article

Evaluation of the Calibration Curve of Water Content Sensors in Iron Ore Tailings

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Abstract

Lately, due to the incidents that occurred in tailings dams in recent years, the Brazilian mineral industry is committed to closure upstream raised dams and, in addition, for the new Tailings Storage Facilities, dry stacking of filtered tailings has emerged as a safer alternative to traditional slurry disposal in ponds. Both structures as a particular characteristic: embankments of iron ore tailings with several meters high and partiality saturated. Considering that, it is essential the understanding of the unsaturated behavior of the tailings for a safe removal and de-characterization of upstream dams and, also, for monitoring the performance of filtered tailings dry stacks. Dielectrics techniques are widely used to measure water content in soil, however, the capacitance probes must be calibrated for each soil type. Iron ore tailings have in their constitution iron minerals such as hematite, magnetite and goethite, those minerals show capacitance influence and could varieties the response of the sensor causing a wrong measure of water content. Thus, it is demonstrated in this work, calibrations curves for Frequency Domain Refractometry (FDR) considering iron ore tailings.

Introduction

Monitoring of geotechnical structures is generally focused on measuring displacements and positive pore water pressures. However, an accurate monitoring of the behavior of many structures and the fact that weather events outside the known pattern have already been observed, has required monitoring variables such as water content and suction using instruments [1-3]. The impacts of climate on geotechnical works can occur as a consequence of the most diverse phenomena [4-9] Particularly important are monitoring on slopes where the critical surface is shallow. Furthermore, monitoring water content is directly related to evaluating the saturation of the material and its potential for liquefaction. Sensors to monitor suction variations (such as tensiometers) are important to consider, but they have some limitations regarding their ability to measure high suctions (> 70 kPa) and the maintenance of such systems. Sensors that make indirect measurements of suction (GMS, Teros 12, among others) have, in general, a very long response time, which, although important for understanding the phenomena, do not allow a temporal association with other events that occur. Thus, the measurement of water content becomes a more objective way of evaluating variations in the presence of water in porous materials. Sensors for measuring water content found commercially (TDR, FDR, capacitive, among others) use principles that are dependent on the mineral in which the sensor is inserted [10-12]. Robinson et al. [13] presented results demonstrating that the presence of iron minerals in the soil, in particular magnetite, can influence soil dielectric constant significantly. Hence, universal calibration relationships, used by some time domain reflectometers, will give erroneous results when employed with soils with high or variable iron mineral contents. In this way, it is fundamentally important to verify the effect of the material where the measurements are to be carried out, on its calibration curve.

Iron mining tailings in Brazil, particularly in the so-called iron quadrilateral in the state of Minas Gerais, have a predominance of the following minerals [14,15]: quartz, hematite, goethite and magnetite. The dielectric constant is the property that the sensors to be used in this study determine to infer the water content of the porous medium. The dielectric constant is the ratio between the capacitance of air and the dielectric material. Therefore, the dielectric constant is dimensionless. Table 1 presents some dielectric constant values of the most common minerals in iron mining tailings in the Belo Horizonte region, Brazil. The dielectric constant is influenced by the following factors: frequency (decreases with an increase in frequency); Temperature (increases with an increase in usual temperature); Voltage (decreases in the presence of direct current voltage); Structure and morphology (it determines the polarization of materials) and most importantly in our case the water content (the dielectric constant increases in the presence of water). Thus, this influences the dielectric constant values). Considering all these variables, it is reasonable and prudent to determine the calibration curve by associating the sensor used with the material where the water content will be determined. In order to have a more precise idea of the meaning of the relationships between the dielectric constants of the materials involved, Figure 1 shows the approximate values of the dielectric constants of the minerals involved in the iron mining tailings. The ratio between them determines the variation of the calibration curve.

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Table 1: Dielectric constant of some mineral.

Mineral	Dieletric constant
Quartz	2.6-4.1
Hematite	25
Goethite	23-36
Magnetite	33-80

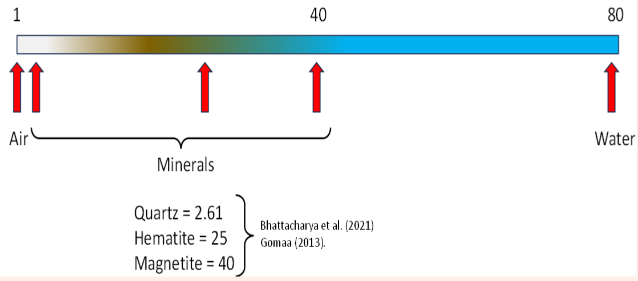

Figure 1: Variation range of the dielectric constants involved in the studied tailings.

Experimental Program

Capacitive sensors (in addition to FDR's and TDR's) infer the volume of water present in the volume captured by the sensor. In this way, the water content that the system infers is volumetric. The gravimetric moisture content (w) (ratio between the mass of water and the mass of solids) can be converted into volumetric moisture content (θ) which relates to the void ratio (e) and dry unit weight (Gs), through the following relationship:

$$\theta = \frac{wG_s}{1+e}$$

Or in terms of dry density (rd): $\theta = w\frac{\rho_d}{\rho_w}$

Several authors present alternative calibration curves to those suggested in the literature or those provided by manufacturers [10,16,17]. The present study verifies the calibration curve of two models of sensors (RK510-01 and RK520-01) manufactured by Rika and presents a specific calibration curve for iron ore tailings from a real reservoir located in Minas Gerais.

Sensors

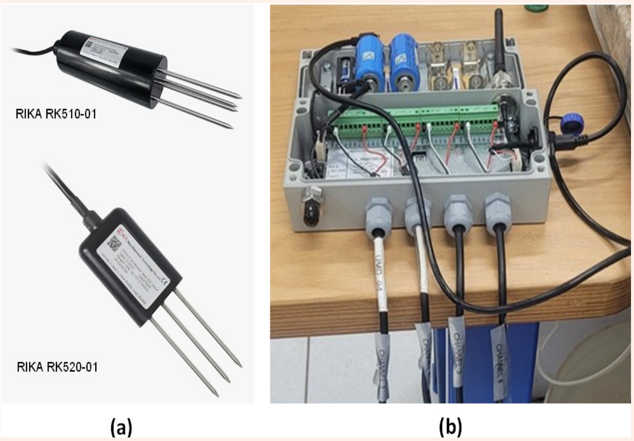

Figure 2: Volumetric water content sensor RIKA humidity sensor Models RK510-01 and RK520-01 and data acquisition used in calibration.

The present study uses the RIKA humidity sensor Models RK510-01 and RK520-01. The sensors (see Figure 2) use an electromagnetic field to measure the dielectric permittivity of the environment, providing an oscillating wave to the sensor rods, which charge, like a capacitor, according to the dielectric characteristics of the soil. The charging time is proportional to the dielectric characteristics of the material, which includes the volumetric water content of the soil. The sensor is designed for field use. In addition to determining the volumetric moisture content, it measures the temperature and electrical conductivity of the material. The sensor and its data acquisition system already include a calibration that reads the data corresponding to the 4-20 mA range and converts the value into volumetric humidity.

The equation provided by the company responsible for the installation is presented below.

$$\theta = (\mathrm{RAW} - 4) * 6.25 \quad \text{Eq. (1)}$$

In which:
θ - Volumetric Humidity (%); RAW - Raw Data (mA)

According to the manufacturer, the equation is general for most soils. Even so, situations should be checked in which the material where the sensor will be used has different mineral characteristics from soils generally found in nature. In addition, it is essential to check if there is any variation in the dry density of the soil.

Materials

For the present study, it was tested three different materials, one is a sand composed predominantly of quartz (IPT Sand), considered as a comparison material, and the other two are iron ore tailings collected in the same TSF (MNV-TS-01 and MNV-TS-04), with a predominance of quartz and iron oxide (magnetite, hematite). Figure 3 illustrates the main components of the tested samples and Figure 4 it is possible to see pictures from scanning electron microscopy (Table 2).

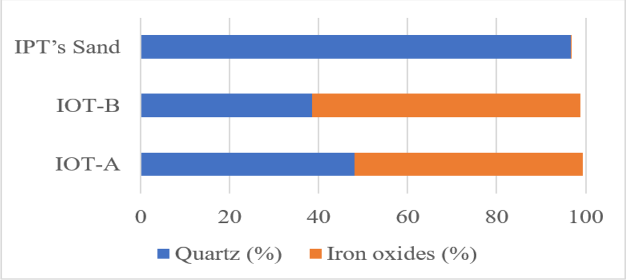

Figure 3: Mineral composition of the materials used.

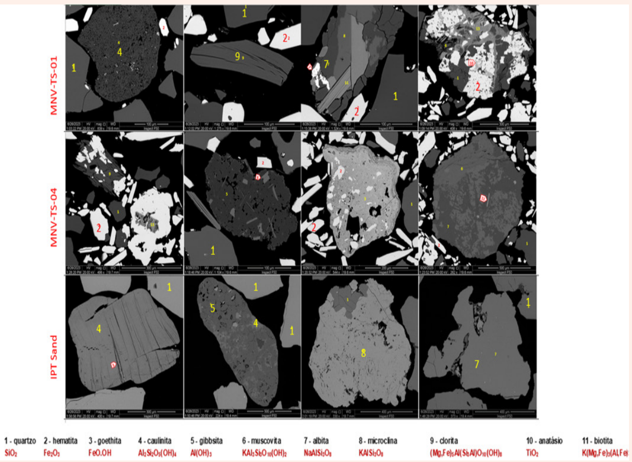

Figure 4: Pictures From scanning electron microscopy.

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Table 2: Table presents some geotechnical parameters of the materials. The unit weight of the materials stands out, ranging from 2,694 to 3,709.

Material	IPT's Sand	IOT-A	IOT-B
Gs	2.694	3.514	3.709
IP (%)	-	NP	NP
wopt. (%)	-	11.93	10.66
gd - max (kN/m^3)	-	21.8	23.1
Coarse sand (%)	91.38	0	0
Medium sand (%)	2.22	20.8	22.27
Fine sand (%)	0.88	55.96	51.68
Silt (%)	4.7	22.25	25.16
% < 2 mm	0.41	0.98	0.89

Methods

The sensor calibration procedure was proposed by Landin et al. [16]. The points for verification and determination of the calibration equations were obtained using a PVC mold with a diameter and height of 19 cm. The materials were compacted with previously established density and humidity. Figure 5 shows the compaction process and the sensor on an already compacted layer. A similar procedure was adopted for tests carried out with IPT Sand.

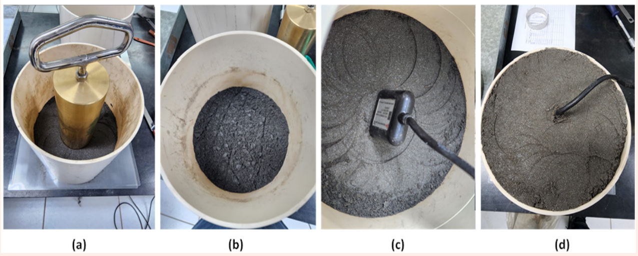

Figure 5: Compression procedure a) compaction; b) compacted layer; c) in placed FDR probe; and d) Final sample.

Results and Discussion

Sensor evaluation

It was verified how the sensor behaved concerning the readings taken in the air, in dry sand, in dry tailings, in a solution with tailings, and pure water. The readings for air, dry sand and tailings provided low values, as expected but indicated a slightly higher value for dry tailings than dry sand. The sensor recorded a reduction when comparing the value of pure water with the solution of water and tailing. In addition, it was evaluated whether there is an influence on the readings due to the sensor's model or the soil's compaction. In each material, readings were performed with two models of sensors. The scatterplots in Figure 6 are grouped by material type and show the results measured with the two sensor models. As shown in the figure, it is impossible to infer any relevant influence due to the type of sensor since the points overlap. Also, no result bias associated with compactness was observed in the graphs in Figure 7 since the readings of dense (e~0.7), moderately compact (e~0.85), and loose (e~1.0) materials overlap.

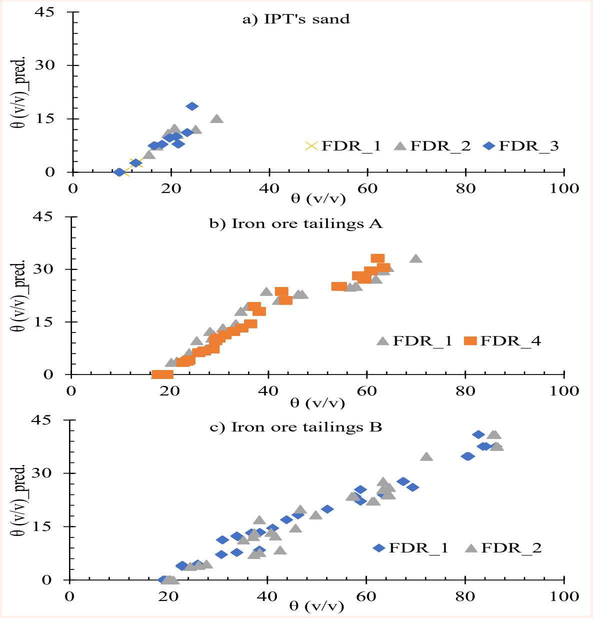

Figure 6: Variability between sensors.

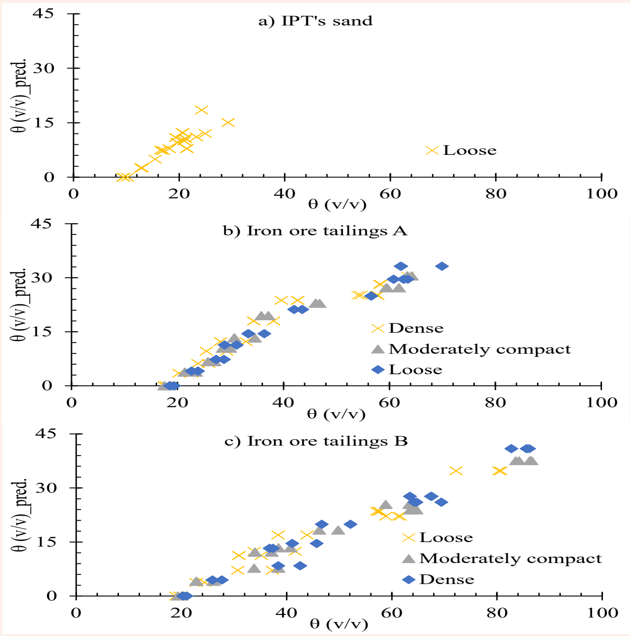

Figure 7: Effect of material dry density.

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Results

The Figure 8 shows the relationship between the actual volumetric moisture content and the value read by the sensor. The dashed line representing the manufacturer's equation. Thus, an error of approximately 20% (gross) will occur when using the original calibration for the iron tailings. The best fits for each material are shown in equations 2 to 4. It can be observed that the data obtained with the sand are closer to the original manufacturer's calibration curve. In tailings, data are all to the right of the initial calibration. In any case did the manufacturer's equation adhere to the experimental results. It is also observed that there is a trend of values more to the right (greater raw data values) for greater density of solids.

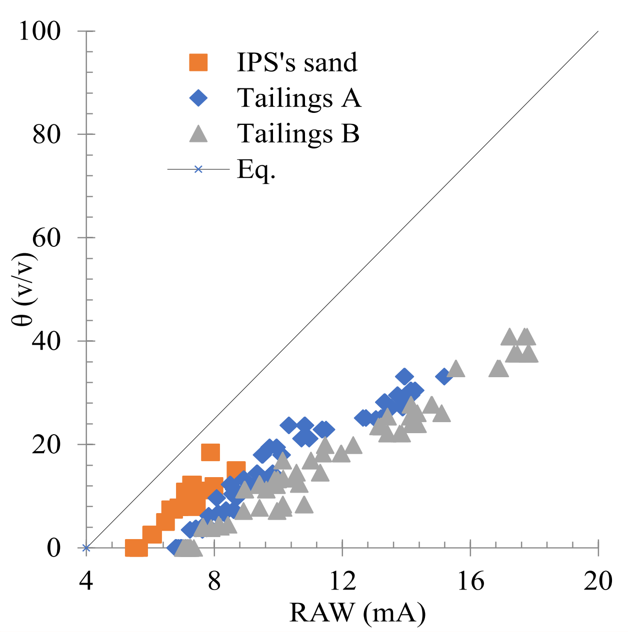

Figure 8: Calibration according to each material.

The following equations represent the calibration curves for the materials tested.

Areia (IPT) $\theta = -33.93 + 6.646\ (RAW) - 0.00847\ (RAW)^2$ Eq. (2)

MNV_TS_01 $\theta = -34.27 + 5.834\ (RAW) - 0.00847\ (RAW)^2$ Eq. (3)

MNV_TS_04 $\theta = -36.11 + 5.633\ (RAW) - 0.00847\ (RAW)^2$ Eq. (4)

It is possible to observe that the points obtained with the residue of intermediate density, with average Gs (3.514 g/cm^3), are located between the other equations. Considering that apparent differences were detected between the two tailings tested and that the difference in density was relevant, whether a new equation could represent the tailings' behaviors was investigated. As shown in Figure 3, the tailings are mainly composed of iron and quartz oxides. The higher density observed in iron ore tailings is directly related to the higher percentage of iron, which, in turn, has higher dielectric constants. In this context, the following equation was obtained by clicking the rate of iron in each sample. Regardless of density, all experimental data can be predicted by the equation 5 with an accuracy of approximately 4% of moisture content. Figure 9 presents the experimental data with the fitted equation.

$\theta\ (v/v) = -318 + 3.78\ RAW(mA) + 3.1\ Quartz(\%) + 2.8\ Iron\ oxides(\%)$ Eq. (5)

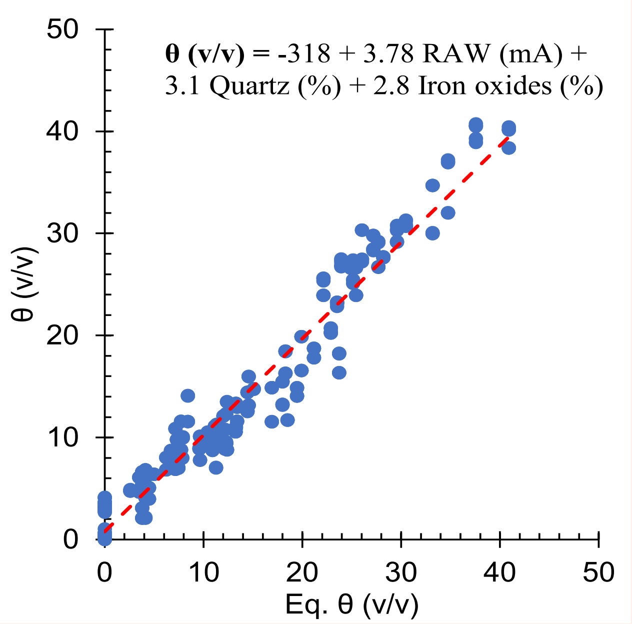

Figure 9: Calibration.

Concluding Remarks

The uses of equipment as the Frequency Domain Refractometry to estimate the water content of soils are very useful in engineering daily practices. However, as discussed in this work, for material with high content of iron minerals, such as iron tailings are, need a certain care for using the equation suggested by the manufacturer. In fact, for this kind of materials, it is suggested to calibrate the equipment using the material in laboratory tests as shown. For Iron Ore Tailings, it was found differences in water content around 20% of error considering the manufactory calibration curve. Using the specific calibration equations, the error is reduced to 4%. An important finding is the effect of the unit weight of the material on the calibration curves.

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